Using Acoustic Emission Technique for Monitoring Real-time Fracture Behavior within Reinforced Concrete Structure Element under Load Test

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Abstract

Stress waves emitted by defect formation or material failure within reinforced concrete (RC) can be complicated in propagation, wave form and frequency modes. However, the acoustic performance can indicate many invisible structural behaviors under loading. In this paper, Acoustic Emission (AE) technique was introduced to digitally record the emitted stress waves in RC-slab and RC-beam specimens during the load tests. Different fracture behaviors, such as Kaiser effect, crack-control mechanism and stress re-distribution, will be evaluated by using these records. Beside the experiment, further application will be discussed.

Keywords: Acoustic Emission, RC structure, Load test, Fracture behavior

1. Introduction

Reinforced concrete is a composite containing aggregates, cement paste and re-bars. When the structure is under loading, stress concentration nearing the pore or pre-crack within the cement paste (weak portion) or the interface between concrete and re-bar may initiate tensile cracking, splitting or de-bonding. These events are all irreversible processes, and create acoustics propagating through the RC material.

Load test is one of the most popular but traditional methods to examine the mechanical behavior of the real RC structures. The test result can be used to qualify the structure in workability or safety. Since most in-site load tests are non-destructive, the embedded defects are hard to be evaluated. To get more reading from the costly tests, AE inspection can be a better approach. However, it is complicated to display the mechanical/fracture behaviors by the massive and complex AE records. This research is addressed to detail these connections using load tests on several structural specimens. Two of these cases are selected and show in this paper with further discussion.

2. Experimental Program

AE technique using NI-based instrument was applied to record the emitted acoustic in RC specimens during the tests. The instrument, specimens and test procedures are briefed as follows.

2.1 AE Instrumentation

An AE system using data acquisition components and real-time programs (LabView7.1) was assembled for inspection. This system provides continually recording (4 digital channel / 800kHz /16bits) up to 4 hours (over the entire load test). The obtained binary data can be displayed and counted for later analysis.

Because of the high decay rate in concrete, acoustics can be damped or distorted during its propagation to the sensor. To get a better reading, more proper sensors with right placement are required. According to previous studies, we knew that the acoustics by fracture of gravel or concrete usually cause higher frequency (50kHz~200kHz) than those by the de-bonding or rubbing between re-bar and nearby concrete (~70kHz). Therefore, the chosen sensor was with 40db integral preamp function and 500kHz spectral response range (150kHz Max.). The acoustics with major frequencies between 10kHz to150 kHz were mainly concerned.

2.2 RC Slab and Beam Specimens

A slab and a beam were produced for the load tests. The RC slab with dimension 2m×2m× 0.125m was simply supported on its four edges for carrying the concentrated load on its center area (Fig. 1). The spacing of D10-rebar mat is 95mm; the strength of concrete was designed as 6000psi.. Fig. 2 presents the beam specimen simply supported for the four-point bending test. The dimension of beam is 0.4m×0.25m×4m; the concrete was designed as 5000psi in strength.

2.3 Load Test and Bending Test

In the load test, four steel rollers placed on fixed steel girders simply supported the slab to against the force. An actuator of a closed-loop servo-hydraulic testing system (MTS) was located on the center of the slab as a concentrated load. To avoid the noise by actuator and to well transfer the loading, a rubber pat (250×250×25mm) was placed between the actuator and the slab concrete. Five LVDTs, mounted on a reference-bar with 300mm spacing, were to measure the vertical deflections while the slab was loaded. The locations of AE sensors are shown in Fig.1,

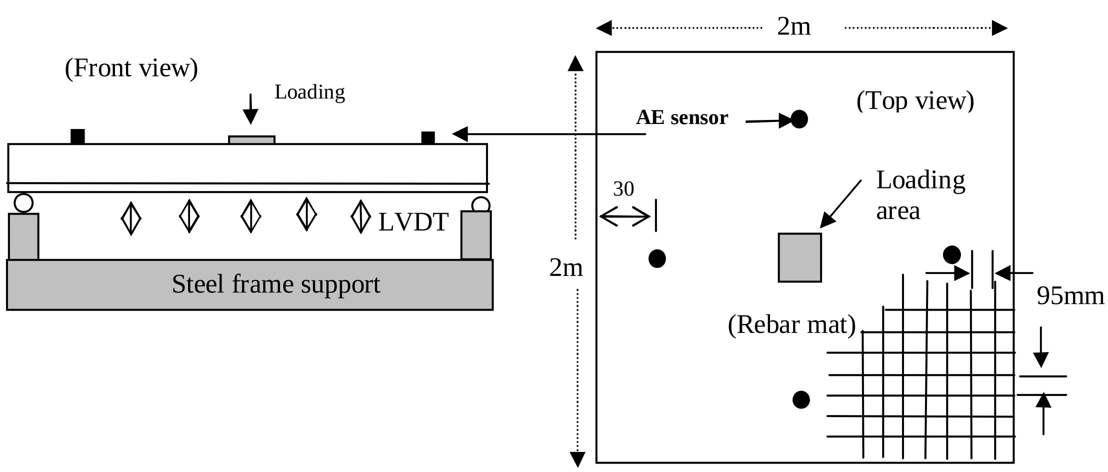

Fig. 1 RC slab and AE sensor locations

where the noise from MTS and support rollers can be quiet down. It also noted that the cracks induced by loading on the bottom surface could not interrupt the acoustics transferring to the sensors on the top surface of slab.

In the four-point bending test, the MTS applied a bending force through a steel girder and two roller-joints on the beam specimen (Fig.2). Under the beam, LVDTs, settled on a reference-bar, were to measure the vertical deflection during the bending test. Fig. 2 also presents the positions of the four AE sensors on the beam. The #1 and #3 sensors were to record the acoustics from the bending cracks in the middle part of beam. Sensor #2 was on the top of the beam, where the compressive stress may cause fracture when the beam went to yielding. Sensor #4, located near the maximum shear force, may record the fracture by shearing.

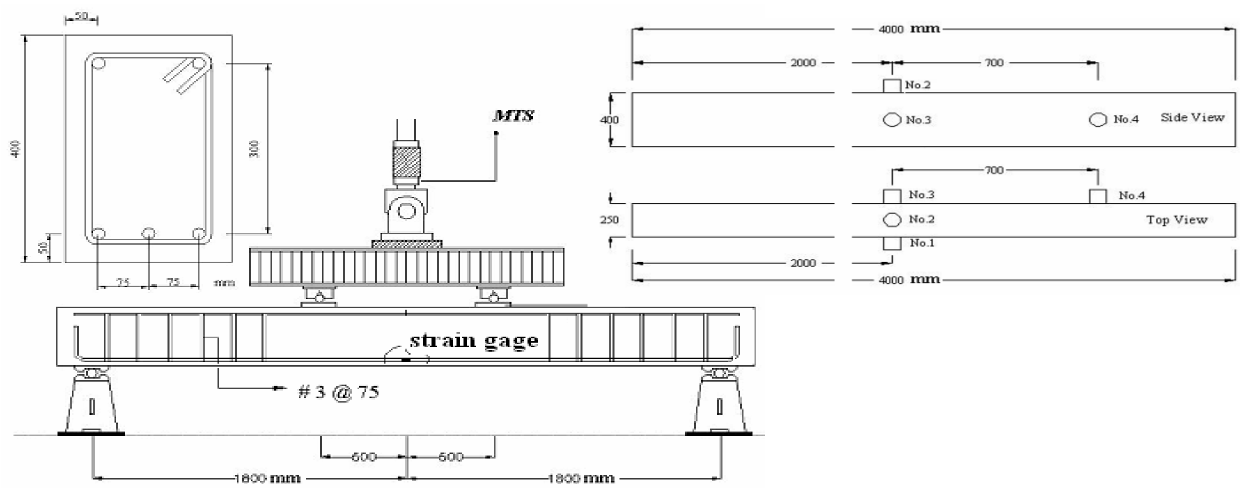

Fig. 2 Beam specimen design, four-point bending test and the sensor locations

3. Case Study: Load Test on RC Slab

The slab test lasted 1680 seconds with an ultimate load 205kN. The maximum deflection was 53mm. The re-bars might be yielding while the slab deformed from 22 to 53mm (loading from 190kN to 205kN). The record of loading and LVDT deflection are shown in Fig. 3.

The first observable AE signals occurred when the loading was about 30kN. Noticeably increasing in signal density occurred after the loading over 40kN. It is noted that an unloading event (190kN~70kN) and the following re-loading happened in the 1197~1466sec. period. When the unloading happened, a bunch of acoustics due to recovery rubbing were recorded and followed by a crack-incubation stage (during reloading). During this period from 1198~1376sec., acoustics kept quiet until the load was up to 150kN. The signal density was back when 170kN was over (1413sec.). This “acoustic silence” can be referred to the Kaiser effect.

The real-time AE record can be performed by counting the number of the times AE signal amplitude over a preset threshold for every second of the test. Fig.4 shows the chart of AE hit count over the load test, where the different line colors are for the different sensors. In Fig.4, two burst emissions were recorded. The first peak at 1197 sec. was due to the unloading; the final rupture in the slab caused the second peak at 1671sec.. Kaiser effect can be found in the re-loading period just after the first peak. We noticed that the hits/sec. rate curves in Fig.4 performed “intermittently” in distribution. This phenomenon might correspond to the mechanical behavior of the re-bar mat. The re-bars restrain the cracks and deformations over the entire loading process. The resistance between concrete and re-bars caused numerous events and signals. However, after each major crack initiation or extension, the energy was released and the brittle fracture of concrete could be hold by the re-bar mat again until the next cracking. Since the loading process was quite stable, the steady increase of energy caused the AE signal with “intermittent distribution”.

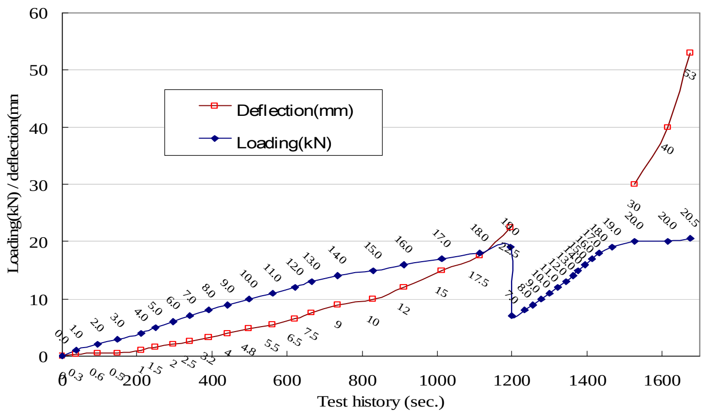

Fig.3 Load and deflection history

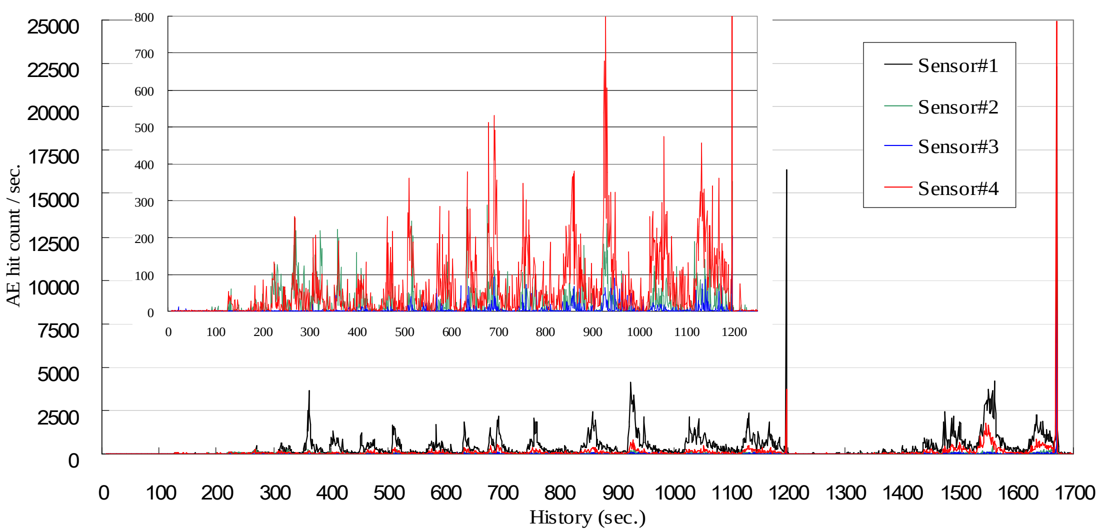

Fig.4 AE hit count per second for over the load test

4. Case Study: Four-point Bending Test on RC Beam

This experiment included two parts. The beam was first bended gradually; then unloaded in a steady rate after yielding. After being repaired, the beam was re-bended as the first time, and unloaded steadily after fracture. The first bending test lasted 1311 seconds. Yielding began at

463sec. with 230kN in loading and 18mm in bending deflection. The ultimate load (239.2kN) came at 683sec. with LVDT reading at 30.6mm. Unloading was proceeded at 708sec..

Fig. 5 shows the chart of AE hit count for the first four-point bending test. Sensor #1 and #3, at the central part of the beam, had received 74.6% and 79.2% of the final hit amounts before yielding; 22.8% and 18.6% in respective during the yielding. In Fig.5, the signal densities of these two sensors increased rapidly after 40sec. (20kN), but turned down and decreased after 114sec. (about 65kN) until the yielding. Since there was no dense re-bar mat in the beam, more acoustics were from the bending cracks rather than the rubbing or de-bonding like the fracture behavior of the slabs. Near the compression region, Sensor #2 had received 38.4% of the final hit number before yielding, but 57.4% during the yielding. It appeared that the major bearing failures occurred after yielding (497sec.). Sensor #4 received 70.2% of hits before yielding; 11.9% during the yielding; and 17.9% in the unloading process. Most acoustics by Sensor #4 were due to the shear cracking. The gradually unloading made the shearing cracks close with steadily rubbing, as well as a steady acoustic performance.

There was no burst emission occurred in Fig. 5. However, two emission peaks need to be concerned. The peak at 114sec. could be due to a major (or initially) cracking within the tension region. The peaks at 497sec. might present another major cracking within the compression region of the beam. At the same time, shearing fracture seemed to be stopped.

The second test was lasted 1582sec. Yielding began at 423sec. with 240kN in loading and 16.8mm in deflection. The ultimate load (246.6kN) came at 640sec. with LVDT reading at 28.1mm. Unloading was proceeded at 1010sec. with maximum deflection 48.2mm. After the beam test, the permanent deformation was about 30.1mm. Fig. 6 presents the chart of AE hit count over the second bending test. Comparing Fig.6 with Fig.5, we note that the AE behaviors were apparently different before and after the repairing. The better flexibility of epoxy might delay new crack extensions. Fig.6 also presented that some major tension cracks (by Sensor #1 and #3) occurred during the yielding while the compression damages (by Sensor #2) progressed. The repairing and epoxy material may change the mechanical behaviors of beam.

5. Conclusions and Future Studies

The AE records of the load tests indicated many significant characteristics in RC fracturing. Most of the acoustic events during the RC slab deformation were due to de-bonding or rubbing but not crack opening. This appearance also occurred in other load tests for different slabs. We found that more acoustics came with “intermittent” distribution when the re-bar mat was denser.

But for different structure, acoustic behavior will be different. In the beam tests, more acoustics were from bending or shearing cracks rather than rubbing or de-bonding by the re-bar mat. The reading from the bending tests might confirm that the loading capacity of the beam after being repaired. But different AE performance indicated that some risk of unpredicted failure appeared in the repaired beam.

Using AE inspection in the load test for real RC structures can revel more evaluation on integrality problems, especially for those under stressing. The application and future studies may be focused on safety-related or high-strength demanded structures. For example, pre-stressed reinforced concrete containment (PRC) with post-tension system (or the tendon system) design is mostly used for nuclear power plant with pressurized water reactor system (PWR) to prevent concrete fracture due to the inside peak pressure. The tendon system results in a distributive pressured state within the concrete of the entire containment wall; however, some parts of this system like the anchor or the bearing plates may cause noticeable concentration load in the concrete. To inspect the embedded fracture, the development here may be useful. The post-tension system has to be checked during a routine in-service inspection (ISI); sometime may have to be re-pulled for the creeping lost. Therefore, ISI program involves loosing, measuring and reloading procedures for the sampled tendons, just like the load tests we monitored. The AE technique could be useful in the ISI.

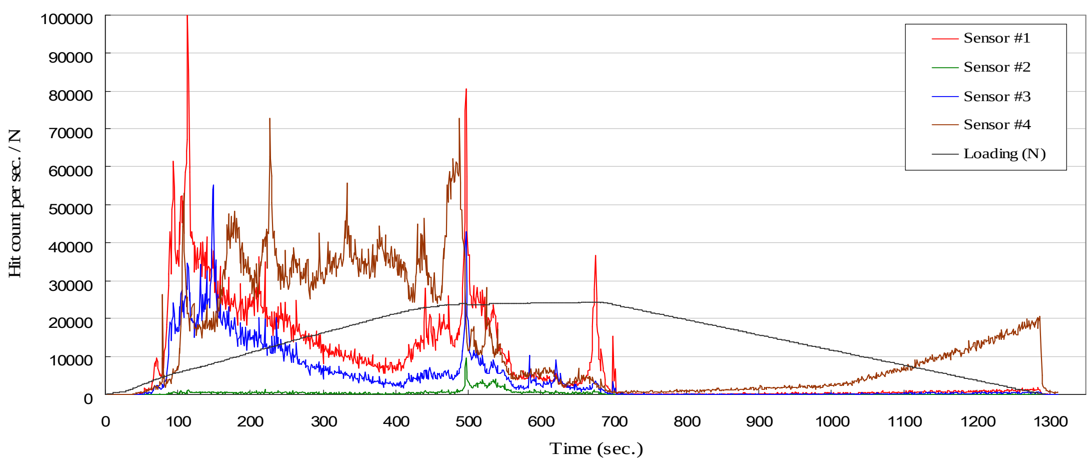

Fig. 5 AE hit count for the first four-point bending test

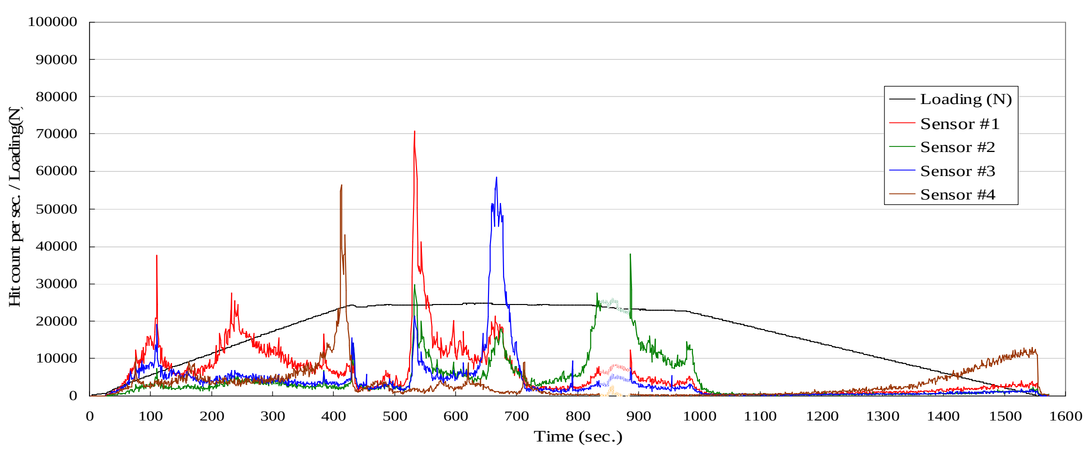

Fig. 6 AE hit count over the second bending test